

# SIMULATION OF ATHEROGENESIS BY COMPUTER DISPLAY TECHNIQUES

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## INTRODUCTION

Most investigators concerned with the pathogenesis of atherosclerosis assume that its occurrence, progression, and possible regression largely depend upon dietary factors. Indeed, clinical programs for the prevention and treatment of atherosclerosis are directed towards the manipulation of serum lipids. There is a considerable body of medical evidence that points toward the importance of blood cholesterol and, in turn, its link to the nutrient composition of the diet. One cannot ignore studies which compared coronary vessels of young Americans killed in the Korean conflict with Japanese control subjects and found equal damage to the coronary elastica (Enos et al., 1955), but which also showed that the latter's lesions evolved into simple scars while the former's lesions developed into continually growing atheromata. In turn, others (Friedman and Byers, 1962) concluded that relative absence of the cholesterol in the Japanese diet was apparently related to failure of the control group's lesions to develop further, whereas the presence of cholesterol aggravated the healing process that is normal to the initial elastica injury, in the American cases.

Genetic history and types of stress have also been recognized as etiologic factors in atherosclerosis; however, they have been emphasized to a lesser extent by researchers. In turn, the relative roles of the vascular wall and the blood flow in vascular degeneration have been debated since the atherosclerotic process was first described. These concepts have been studied to even a lesser degree. It is this investigator's contention that localization of the atherosclerotic process is determined to no mean extent by rheologic factors, including the geometrics of arterial branching, intraluminal pressure and pulse contour properties of the blood and blood-intima interface, and the physical properties of the vessel wall. Amplifying this contention, the vascular wall should be regarded as having a strong role in the initiation of vascular degeneration as well as in the later manifestations of such localization as seen clinically (Reemtsma et al., 1970). Others (Mustard et al., 1964; Downie et al., 1963) recognize a multitude of interactive mechanisms that include hydraulic factors and arterial wall changes. Fluid mechanics may play a part in the localization of lesions (Texon, 1957, 1960 a,b). The role of hydrodynamics has been emphasized as one sees an irregular distribution of atherosclerotic lesions upon vascular walls (Wesolowski et al., 1965). Experimentally, some investigators (Lynn et al., 1970) have sought to obtain a vorticity map of the aortic bifurcation region while others (Spurlock and Durfee, 1968) studied dye streamlines in pulsating flow. Recently, hemodynamic theories of atherogenesis have been reviewed (Gessner, 1973) and the relative merits of

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pressure-related, wall shear stress, turbulence-related and flow separation hypotheses have been examined.

The study of flow-related hypotheses has been extended by the present investigator in an attempt to develop simulations of clinical phenomena. Such simulations are the end products of mathematical analyses of the blood flow field, and are useful to avoid large amounts of unwieldy data emanating from equations that are intractable except in particular, well chosen situations. The resultant representations are made available through the employment of computer graphics. This tool allows depiction of a physical system on television screen and permits the viewer to interact with the natural appearing representation. This paper will present a feasibility study of the attempt to study the development of a coronary atheromatous lesion and subsequent blood flow changes. Eventually, this new investigative effort should allow the investigator, with the aid of a computer, to *walk into a simulated artery and watch the lesion grow with time.*

## 2. COMPUTER GRAPHICS: ITS ROLES IN THE PROJECT

A small computer, acting as a satellite to a larger computer some distance away, is employed. (See Figure 1) The smaller computer processes data from the cathode-ray-tube (CRT) screen, gathers data to present to the larger computer which has greater capability, and acts as a multiplex system for display information coming from the other computer. (A

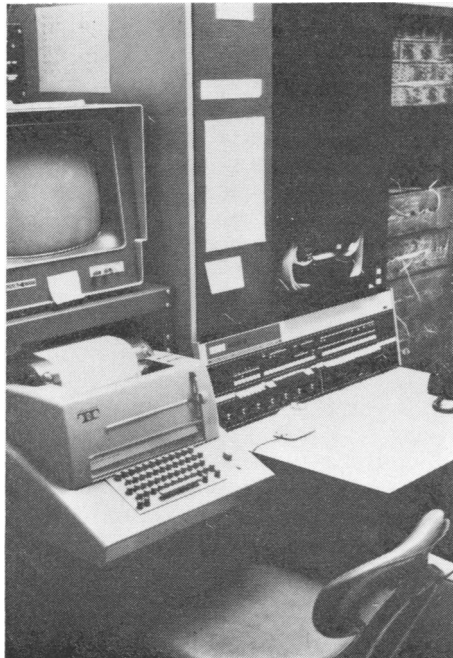


Fig. 1. Computer graphics display equipment.

multiplex system transmits several signals simultaneously on the same circuit or channel.) Therefore, several satellite computers can be attached to the "mother" computer, allowing many investigators at separate Teletypes to work at individual problems simultaneously.

A teletype allows the investigator to type in his computer program to the storage banks of the computer and then issue commands to the computer such as input of data and output of desired information. A small white box, termed a "mouse," is a graphical input device consisting of a plastic unit in whose base 2 potentiometers are mounted. The mouse rests on 2 metal wheels, whose axes are at right angles to each other. As the mouse is rolled on a flat surface its movements in the orthogonal directions are recorded by the rotation of the potentiometers and an electric beam moves accordingly on the display screen. Pressing a button on the mouse allows information transfer regarding location of contact at the dot between the computer's memory bank and the teletype. The computer interprets commands from the teletype concerning the dot position and constructs a drawing or deletes a geometric section as required, or displays numerical data upon the screen. Once a representation of an object is upon the screen, clever subroutines within the computer program can, by employing matrix algebra concepts, cause the object (in perspective view) to rotate or translate its position, continually or by single frame, so as to allow complete scrutiny. Shading and even coloring of the object are possible. As in most fluid flow analyses, contour maps are used to present the data in pictorial form. The contour mapping routine designed for this interactive graphics simulation program is more efficient compared to other contour mapping routines available. The contour program is designed to plot unlimited numbers of contour levels.

The use of contour maps to represent data on a two-dimensional grid, however, is rather insufficient. Ambiguities arise when the contour levels are not labeled with their associated values, for computer graphics displays have a limited view area. In addition, depending on the contour levels used, detailed information may be concealed between contours. To utilize fully the computer graphics resources, an isometric display program was designed to supplement the contour maps. The isometric plot maintains the spatial relationship of each data point on a plane and uses the third axis in three-dimensional space to represent the functional values. The data array is represented by a family of curves, each representing a set of data points along one dimension in the data array. Each curve is plotted where it is not hidden by any of the curves previously plotted. The sequence of curves thus closely approximates a surface which represents the data array. In order to provide spacing between successive curve profiles only every other curve profile is displayed in all isometric plots.

The combination of contour map and isometric view provides description of the solution. These displays, however, do not indicate the numerical values of the data at any point. In order to facilitate detailed examination of the solution, an interactive curve plotting program was developed. It allows the operator to examine the data values along a selected cross-section in the solution space. To select a particular cross-section the mouse, used as an input device, is brought to the desired position on the contour plot. When one of the three buttons on the mouse is depressed, the current location of the electron beam is transmitted to the program. The data along that cross-section is plotted on a grid; and a dotted line is drawn on the

contour map to indicate the location being examined. The grid is scaled appropriately by the program to ensure inclusion of all possible values. The operator has the option of displaying a particular curve or a family of curves for comparison. Results of this methodology are seen subsequently.

### 3. THE SIMULATION PROCEDURE

In the attempt to analyze the movement and consequential change of the blood flow field about a lesion, an idealized projection of an isolated protuberance was placed on a boundary wall, as shown in Figure 2. The obstacle and its surrounding flow field was then covered by a cellular network which can be described as a computational mesh; the coordinate values of each cell node were described to the computer and then stored in its memory. The Navier-Stokes equations that prescribe the two-dimensional flow (Greenfield, 1972a) about the obstacle on the wall were simplified by the use of the finite difference method (Fromm, 1963; Fromm and Harlow, 1963; Pearson, 1965). Such action allowed the extremely difficult, nonlinear equations to be simplified, resulting in a set of algebraic equations that were compatible with the computer. These approximations related the value of the dependent variable at a point in the computing mesh to the values at a number of symmetrically arranged neighboring mesh points, at one instant of time and then at succeeding time intervals. The solution becomes quite accelerated if the method of relaxation is used (Lawrensen, 1966). The approach made use of stream function and vorticity function values at each cell node after proper manipulation of the equations. The procedure was first attempted for obstacles that were parallel to the mesh boundaries (Greenfield and Brauer, 1969) since crossing the mesh lines was somewhat of an additional mathematical problem. A later and improved procedure allowed non-parallel results. This latter development was extremely important for it allowed the positioning of side chan-

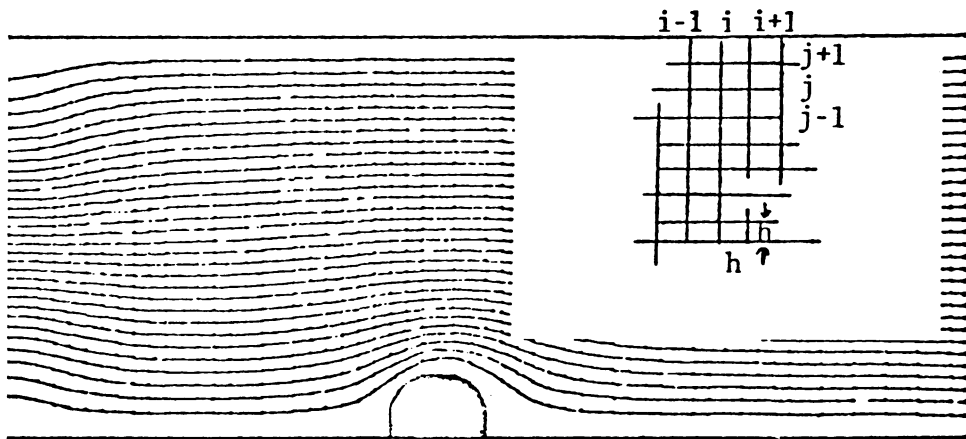


Fig. 2. Idealized lesion on an arterial wall, overlaid by a computational mesh. Streamlines have been formed.

nels that start at the boundary wall. Blood flowing through a large channel such as the aorta could then have its path simulated as it moved into any smaller channel of the arterial tree. Although not discussed in this paper, the methodology has also been employed for analyzing the motion of occluders in prosthetic heart valves and the resulting sequence of events (Greenfield, 1972a,b; Greenfield and Hampton, 1973).

The computer program that allowed the above results contained sub-routines that formed a horizontal velocity plot, a vertical velocity plot, a total velocity plot, a stream function depiction, the velocity vector form and a vorticity function display. The computer program also included a subroutine so that a hard copy of a single time frame of any plot could be drawn upon an automatic plotter.

The first group of flow studies that evolved proved the feasibility of the concept. As the investigation continued, specially employed numerical techniques permitted the fitting of curved boundaries into the desired two-dimensional flow problem. Again it was felt, however, that the methodology should be improved in order to bring the analysis technique closer to the situation *in vivo*. At this point the technique for forming the desired displays used vorticity and stream function values, as noted, for the primary dependent variables. Some disadvantages of this technique were inadequate eventual extension to three-dimensional studies and the difficulty encountered in satisfying free surface boundary conditions. Also, true channel flow remained to be described and pulsating motion and viscoelastic properties of the arterial wall were missing in the final solution. To overcome partially these difficulties the Marker and Cell method (Harlow et al., 1966; Amsden and Harlow, 1970) has been studied and simplified. This method uses pressure and velocity as primary dependent variables and permits free surfaces; the latter useful for analysis of a pulsing, viscoelastic wall. This method also maintains accuracy with a minimum of computer time through the employment of a corrective procedure in the computer program. Stress equations were also programmed so as to enlarge the simulation capabilities.

The next section includes some of the results and explanatory comments of concern to parametric studies of an idealized lesion. These accomplishments will then be fitted into the larger study that involves processes for investigating the coronary arterial section that encloses the lesion.

#### 4. LESION-PLAQUE SIMULATION STUDIES

Atherosclerotic lesions may be classified into three types: fatty streaks, fibrous plaques and complicated lesions. In the following simulations the terms lesion and plaque may be arbitrarily interchanged since the obstacle studied is an idealized one, in no particular stage of development. No detailed meaning is, therefore, given to the obstacle at this point.

For the sake of simplicity the first attempt to simulate an idealized lesion (or a plaque) was computer processed as if it were the hemisphere noted in Figure 2. The numerical technique that employs the vorticity and stream function as prime parameters permitted results as exemplified in Figures 3a-d. Figures 3b and 3d show the vertical velocity and vor-

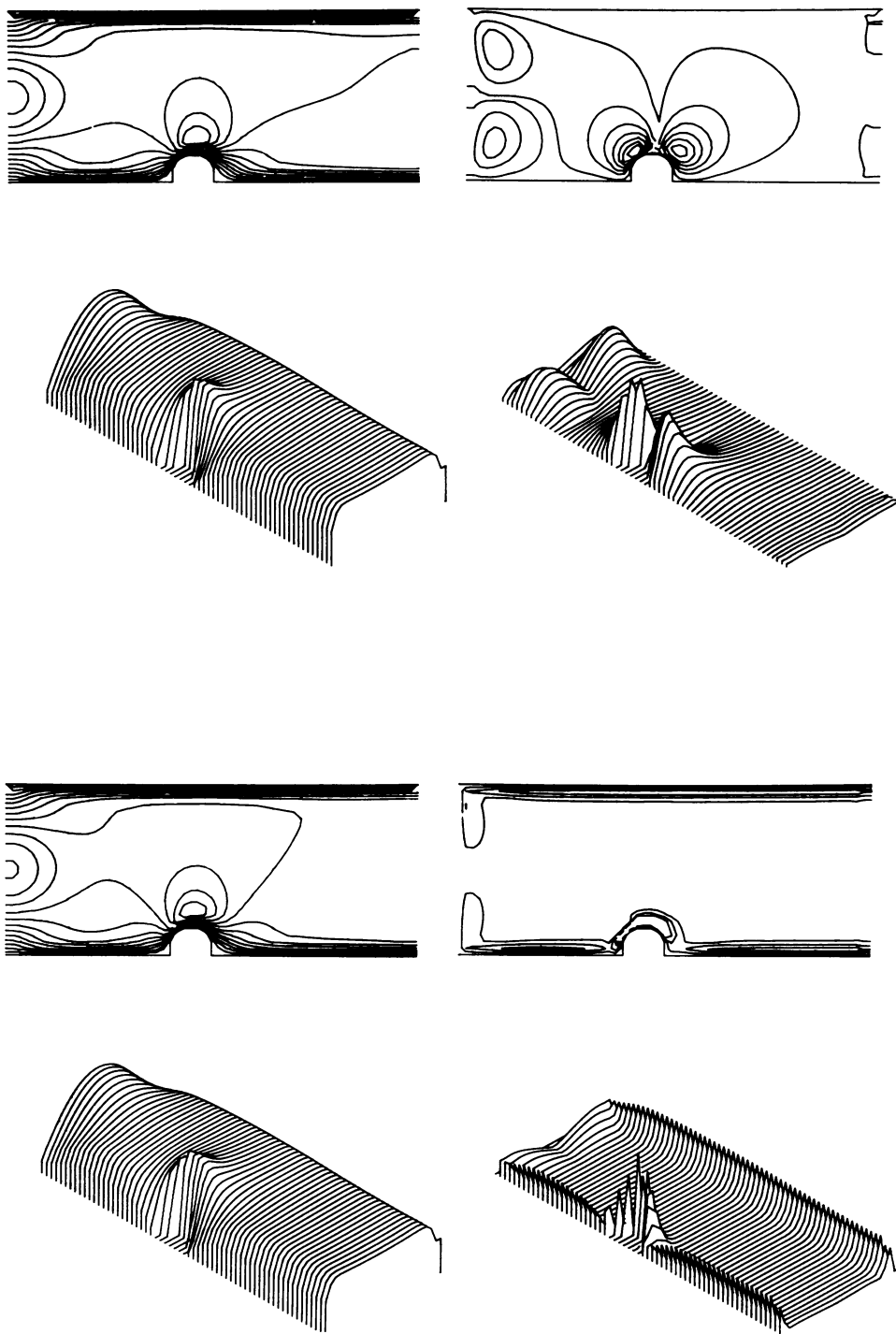


Fig. 3. Various computer devised flow functions for an idealized atherosclerotic lesion.

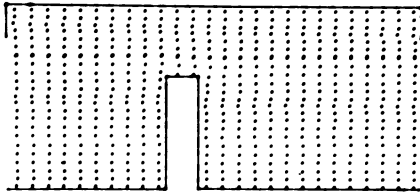
ticity plots (Greenfield and Brauer, 1971) at one particular time frame and for a particular Reynolds number in their respective continua of motion. (The Reynolds number is a dimensionless number, indicative of the ratio of flow inertial forces to viscous forces, and including the flow velocity as a parameter.) The reader will note that emphasis is placed throughout such studies on the vorticity function. If vortices are assumed to be the forerunners of turbulence and denote the positioning of eventual turbulent flow areas, and turbulence can possibly denote shear stresses and development of mural thromboses (Sako, 1962; Scharfstein et al., 1963), such theoretical studies are of interest. Burns et al., (1959) discussed the possibility of turbulence inducing high frequency vibrations, which may, in turn, induce a destructive effect upon the arterial wall. Subsequent healing at the turbulent position might be viewed as the predecessor of a lesion. If one views Figure 3d as an interim step in the formation of an idealized lesion, the isometric view shows the sharp peaks of turbulence and at what points an involved vibratory motion should be amplified.

Figure 3b evaluates the velocity component pictorially along the y axis and shows increased lateral values for the incremental time frame chosen. If one compares the isometric plots of Figures 3a and 3c, the horizontal and total velocities, it is seen that they appear equivalent. This would lead one to believe that since the total velocity is the vector sum of its horizontal and vertical components, the vertical velocity is quite small.

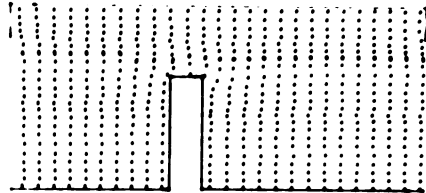
In an attempt to vary the shape of an idealized plaque radically, a square form was drawn upon the graphics display screen rather than the previously seen hemisphere. This presumes that the investigator can draw any interim shape between the two extremes and then employ either numerical procedure. To exemplify this the second numerical procedure was initiated in order that the blood flow be represented about the square plaque by particles. As seen in Figure 4, regions were opened to allow inflow and outflow in the flow regime. At a particular time in the sequence the observer can see a vortex forming downstream and proximal to the obstacle tip. Subsequently, as the blood flow velocity increased the flow became disoriented and randomly turbulent. (The obstacle shape was enlarged in the y coordinate direction to also study flow about a disc-type occluder tip in a prosthetic heart valve in other studies.) The procedure was then varied so as to view the flow about a hypothetical idealized square plaque in a half-filled channel. Figure 5 depicts a group of one-time-frame examples of the resulting continuum (Greenfield, 1973; Greenfield and DeBry, 1972). Such particle motion in a partially filled channel permits a free surface boundary to be duplicated, rather than the previously noted rigid wall boundary. Space does not allow the display of all the shapes that were studied and that were bracketed by the hemisphere and square as advanced lesion models.

A particular study chosen to follow the above one was a shear stress simulation. It has been suggested that a localized change in pressure or shearing stress (Rodbard, 1958) may trigger certain biological mechanisms that allow proliferation of the endothelial and subendothelial cells of the arterial wall. Fry (1968, 1969) has examined the influence of local wall shear levels on the erosion of the endothelium and has attempted to correlate high wall shear stress with common sites of lesion development. Although at least one investigator (Caro, 1971) has opted for lesion development in regions of low wall shear, in part because of a shear-dependent

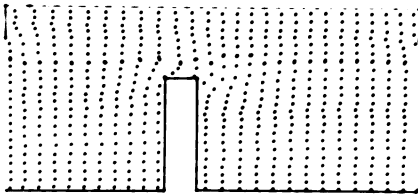
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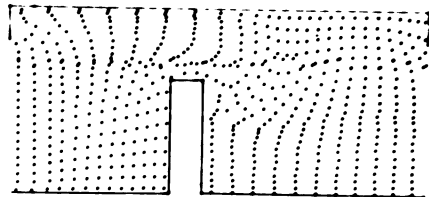
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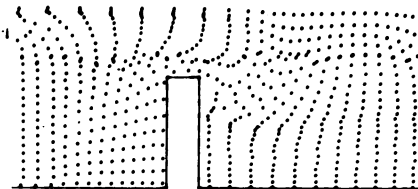
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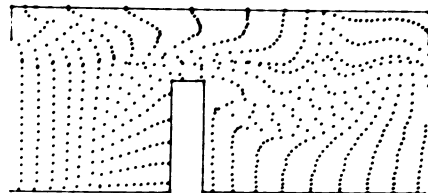
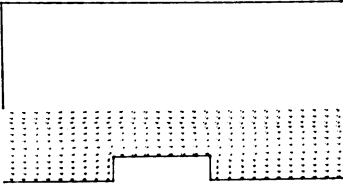
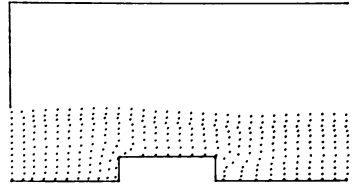


Fig. 4. Successive views of simulated blood flow, represented by particles, about an arbitrarily shaped obstacle.

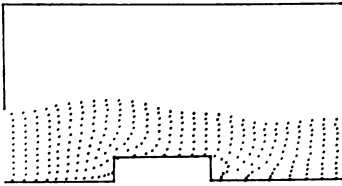
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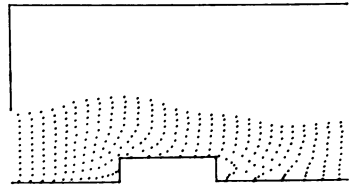
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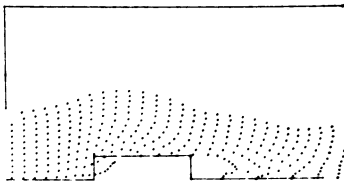
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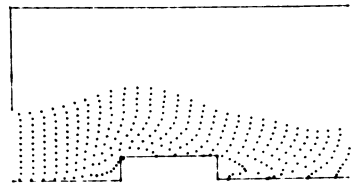


Fig. 5. Successive views of blood flow simulated by particles, employing a free surface boundary.

diffusional efflux theory, the important point is that this investigator felt that shear stress studies should be simulated. To this end, an atherosclerotic ring or "plug," as portrayed in Figure 6, was assumed. Later, an asymmetric "plug" was studied.

A finite element approach (Ray and Davids, 1970) was used to analyze and then simulate blood flow in the inlet region of a tube when a "plug" was present (Cannon and Greenfield, 1972). Interest was aroused since the analysis could be extended to the viewing of blood flow velocity profiles and stress distributions about symmetric and asymmetric atherosclerotic plaques. Accuracy tests performed by Ray and Davids and the author indicated that the methodology allowed results that were within 3-5% of previously accepted solutions.

The applications of the finite element method permitted the arterial section to be divided into contiguous planes, each of which were then divided into cells. Any number of cells were allowed (in cross-section) to be part of the plaque, however, no blood was allowed to flow "mathematically" through the plaque section. One assumed a rigid, constant diameter tube where there was no plaque or lesion. Other assumptions were laminar flow, a Newtonian fluid and insignificant radial velocity.

The side and end areas of each cell and the mass of the contained blood were calculated. The forces acting on the cell's sides and ends, resulting from the flow from the inlet region and the retardation due to viscosity, were calculated so as to form fluid velocity values in each cell. Blood within the artery section was assumed to be initially at rest except for the entrance region cells where an initial velocity was assumed. A no-slip boundary condition imposed the constraint that blood in cells near the wall of the artery and the lesion surface had zero velocity. The numerical process, programmed for the computer and the simulation display output, was an iterative one. With the initial flow condition stated for the inlet region the computer program permitted each successive iteration to yield the blood velocity within the individual cells in each of the contiguous planes.

The above approach permitted the investigator to command the computer to display the fluid velocity at each "cell" in the vascular vessel. In turn, this evaluation allowed the simulation of the velocity patterns (based upon chosen Reynolds numbers) and the shear stress distribution resulting from the blood flowing past an asymmetric plaque or through a symmetrical plaque; the latter constituting a plugged arterial section. Associated with each velocity profile was a value of the shear stress between the fluid of that particular plane and the vessel wall. These were assembled into a second display file and arranged to appear as a graph above the velocity profiles. The pressure gradient appeared at the bottom of the picture.

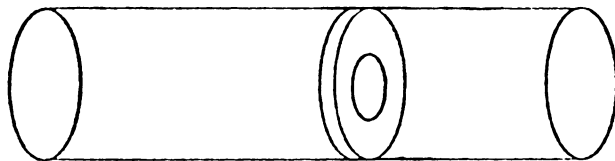


Fig. 6. A simplified arterial "plug".

Figure 7 shows the simulation of the blood flow's velocity profiles, by particles, when no lesion is present. Notice that the shear stress and pressure gradients appear as one might assume such functional shapes to be for the inlet flow region position. Figures 8, 9, and 10 show the blood velocity profiles when a symmetrical plaque was present at different vascular channel positions and with varied plaque lengths. The user of the display system is able to position the plaque and change its length at will with the aid of the light pen or mouse at his disposal. Not only can the investigator, via the teletype, specify the position, size and shape of the plugged region, but he is also able to create it one layer at a time and subsequently view flow parameter changes as the plaque builds up.

It soon became obvious that the observer, looking at the screen, might confuse velocity profiles as the dots became irregular, particularly where the profiles changed shape in the plugged section. In order to ease the situation the particles that made up each velocity profile were connected via cubic splines (Ting and Greenfield, 1972; Greenfield, 1973); third-degree polynomials that are fitted to a set of data points. Such a procedure necessitated each velocity profile to have eleven times as many data points which, when connected, formed pleasantly smoothed curves, as shown in Figures 11 and 12.

As noticed, the blood velocity profiles of Figures 11 and 12 were symmetric curves, for no atherosclerotic plaque was deemed to be present. Figure 13 depicts the result of placing a relatively thick, square edged, axially symmetric obstruction in the flow field. Since that section of the flow field that is displayed may not contain the stenosis, that obstructing shape in cross-section was made to appear at the upper right boundary of the artery. It is realized, however, that for analytic purposes the computer reads the plaque position as being in the inlet flow region. Viewing the plaque as a cross-sectional shape allows interaction by light pen to change the shape. Shown on the screen is the maximum shear value on the plaque, when

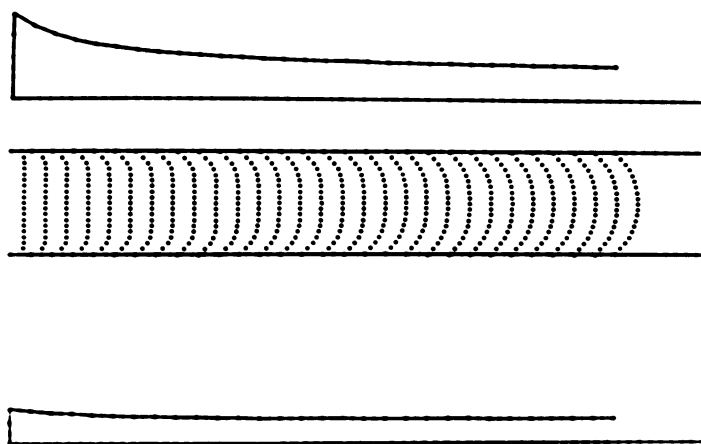
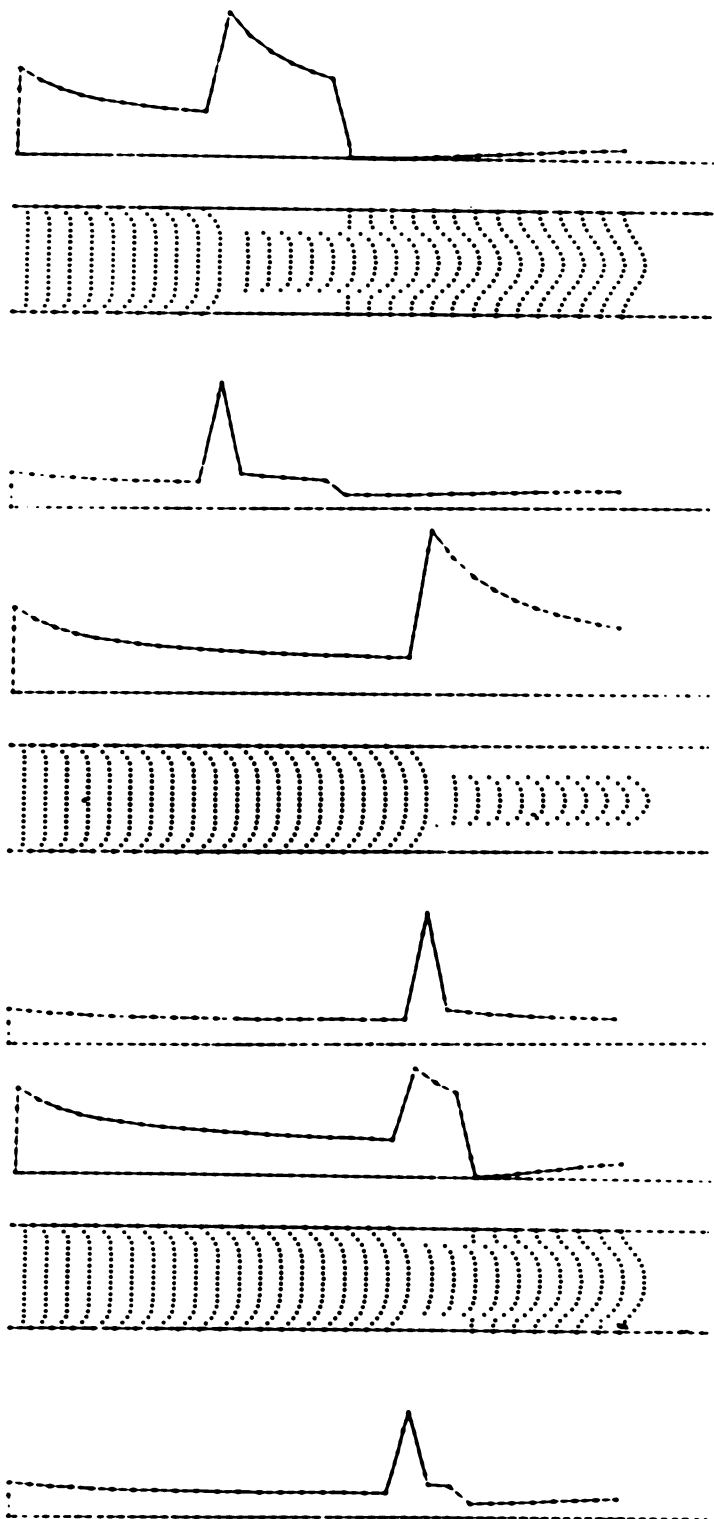


Fig. 7. Arbitrary velocity profiles of simulated blood moving in an arterial channel with no atherosclerotic plaques present. (Shear stress gradient and pressure gradient are also shown.)



Figures 8, 9 and 10: Arbitrary velocity profiles of simulated blood moving through a symmetric atherosclerotic plaque in an arterial channel. Top view in each computer-formed display is the shear stress gradient, center view is the velocity profile group and the bottom view is the pressure gradient. Values change as plaque is lengthened and flow velocity is changed.

along with the percent of shear increase at that position compared to shear stress at the inlet. With the shape changed to a triangle the shear stress values changed, as seen in Figure 14.

The observer is also presented with numerical values of erythrocyte damage upon the display screen. Such values were seen to change with the

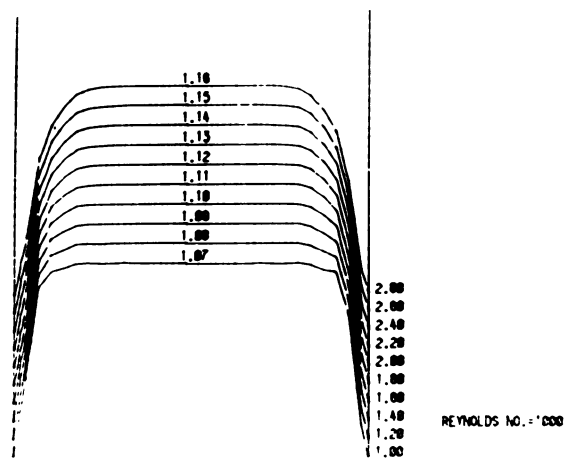


Fig.11. Cubic spline representations of blood velocity profiles just distal to the inlet region of a vascular channel, (no plaques present). Velocities are presented as multiples of initial velocity; distances at the right as multiples of channel diameter.

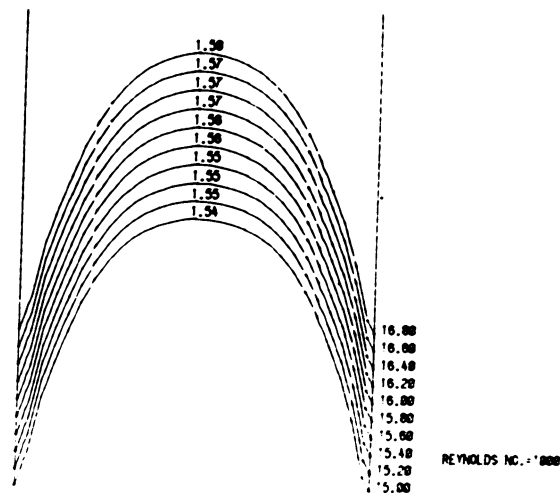


Fig. 12. Cubic spline representations of blood velocity profiles in region of fully developed laminar flow (no plaque present).

reshaping of the plaque at the inlet region of the flow regime. The red blood cell damage calculations were based upon the empirical studies (Nevaril et al., 1968) of others. Nevaril subjected thin layers of blood to varying degrees of shear stress and tabulated the resulting cell damage. In the present analysis, the outermost layer of fluid was assumed to correspond to the thin layer postulated by Nevaril. At the point of maximum shear

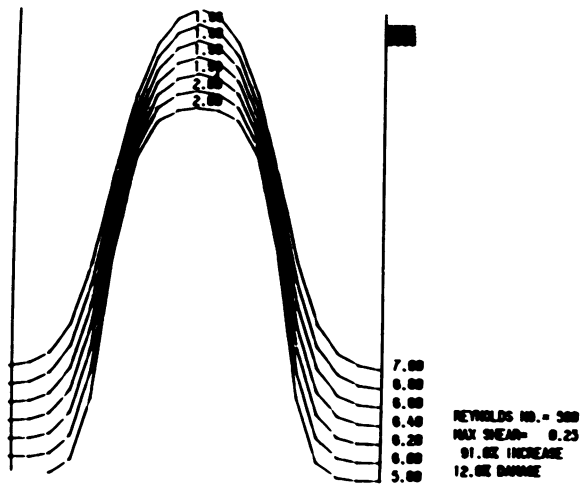


Fig. 13. Blood flow velocity profiles, downstream of a square-shaped annular obstruction.

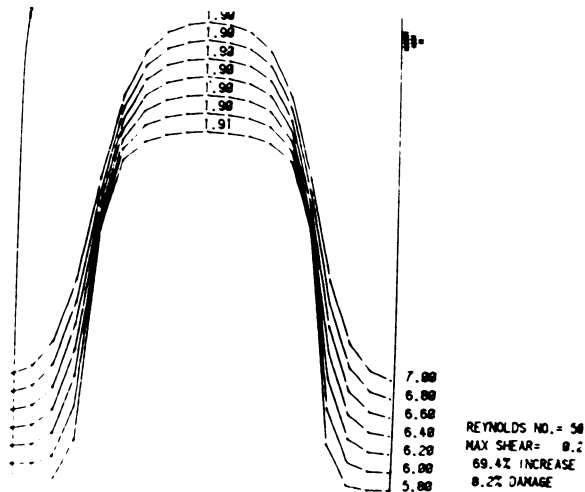


Fig. 14. Blood flow velocity profiles, downstream of a triangular, cross-sectional-shaped annular obstruction.

upon this layer, the corresponding damage was calculated according to Nevaril's results. This yielded the percent of blood cells damaged in that layer of fluid. This quantity was then multiplied by the percent of total vessel volume occupied by the outermost layer of fluid and stored in a display file. Although the total area causing the shear stress is not nearly as great as that used by Nevaril, it is believed that results are approximately correct, for Nevaril stated that findings were essentially independent of the duration of the shearing stress.

Figure 15 resulted when the case of an asymmetric lesion was programmed as being present at the inlet region and on the left wall. It is obvious that with no lesion component present on the opposite wall the velocity profile will be unaffected at that position.

Up to this point the reader has been presented with simulation capabilities that, by computer programming, permitted the analysis of various parameters about an ideal lesion or plaque, but only at a particular point in the growth cycle. It will now be seen that the simulation procedure can also be performed with the idealized lesion placed in a larger flow regime—a particular length of the arterial tree. As seen below in Figures 16 and 17 the advanced lesion was viewed as being present in a renal artery as well as in the abdominal aortic bifurcation (Greenfield and Brauer, 1971). Again, space requirements preclude the display of all the computer results except the vorticity function plots. The renal artery result was varied so that the flow velocity increased in the proximal renal artery. This permitted the formation of a montage, seen in Figure 18, that showed the change in the growth of a lesion with increased flow velocity. The renal section and the aortic bifurcation were also joined for simulation of that connected regime (Greenfield and Kolff, 1972).

The renal artery simulation was programmed so that the side channels

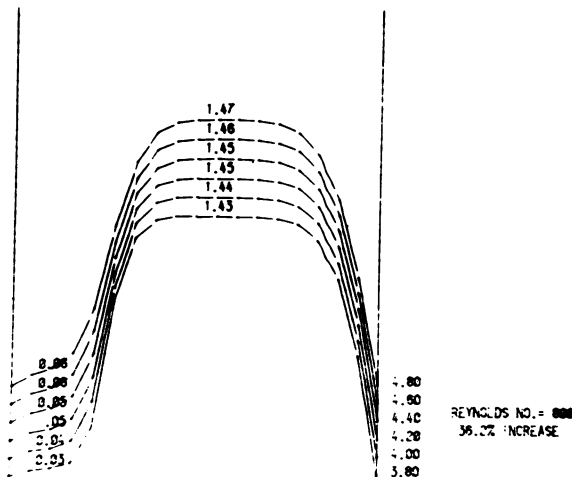


Fig. 15. Computer-simulated blood flow velocity profiles, downstream of the inlet region of a vascular channel, with a square-shaped asymmetric plaque present.

angled at any desired inclination. The proximal artery was seen to face upstream slightly to conform to displacements seen in angiograms. The capability of arbitrary angling allows the input of angiogram-derived patient data to show the amount of turbulence and possible resulting thrombi, compared to the amount of angle variance from the main blood flow.

Although not shown, the plotted stream function for the renal arteries bore out physical concepts in that the streamlines were shown closer in proximity upstream of the side arteries, therefore, permitting a lessening of flow energy downstream as flow is drained off in the side channels. The horizontal velocity plot showed the typical parabolic front for laminar flow which then changed to a typical turbulent front in the main flow region between the side arteries. The total velocity plot again showed a proper physical amalgamation of the horizontal and vertical velocity components. The vorticity function, seen in Figure 16, became the subject of detailed sequential study within the particular portion of the backward facing side artery region, resulting in Figure 18. Figure 16's isometric plot

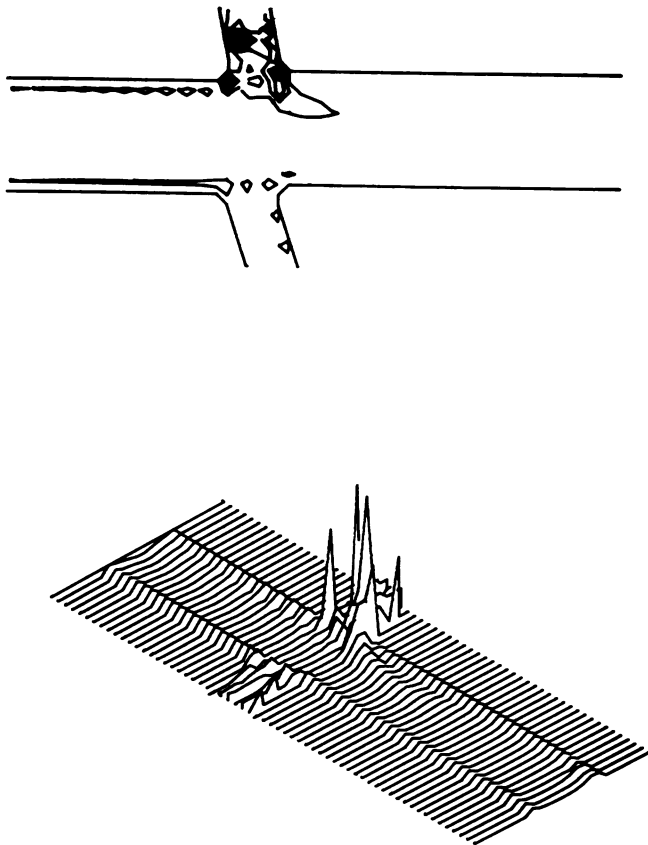


Fig. 16. Computer-simulated vorticity function plot for angled renal arteries. Isometric view shows variances in vorticity peaks at different positions.

in particular, shows the extremely high vortex peaks in the upper channel, which was to be expected as the blood flow radically changed direction. Realizing this, the Reynolds number was continually changed in the montage components of Figure 18 to allow a transition from a slow initial rate of flow to slightly above an average blood flow velocity value in that particular area. One then notes the formation of a vortex in such a velocity regime and if the observer views the small triangular shaped vortex on the anterior wall, the breakup and reformation of stream function lines in amplifying this vortex are clearly noticed.

In turn, comparison of Figure 17 with the arterial tree and its usually seen lesion sites shows that the theoretical vorticity function plot appears equivalent for site positioning with observed atherosclerosis sites.

## 5. INTERNAL VIEWING OF THE ARTERIAL TREE

With the study of the single advanced lesion amplified to the point at

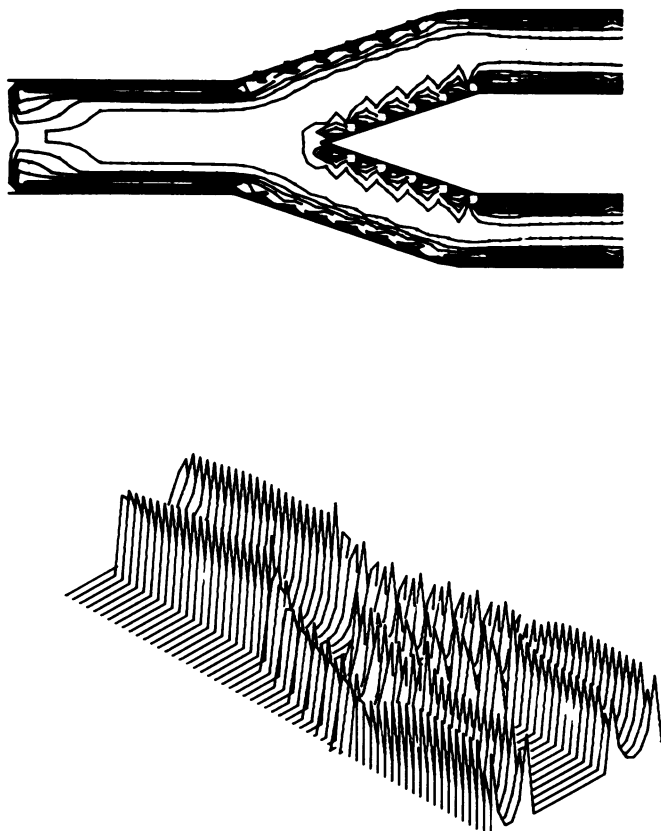


Fig. 17. Computer-simulated vorticity function plot for the abdominal aortic bifurcation.

which it is viewed in situ within a section of the arterial tree, a desirable second amplification would be the viewing of the affected area as if the viewer were located inside the artery. Since the investigation at hand is a simulation procedure it is obvious that such internal viewing would also be simulated. Such three-dimensional kinematic behavior has been duplicated by the employment of a head-mounted display helmet which includes two miniature ( $\frac{1}{2}$  inch square) cathode-ray-tubes (Sutherland, 1968). The computer-developed information, previously seen on the normal-size display screen, is now displayed upon the two miniature screens placed in tubes centered before the observer's eyes (see Figure 19). An incorporated optical system presents a stereoscopic image of the simulated data so that computer-projected objects enter and leave the observer's field of

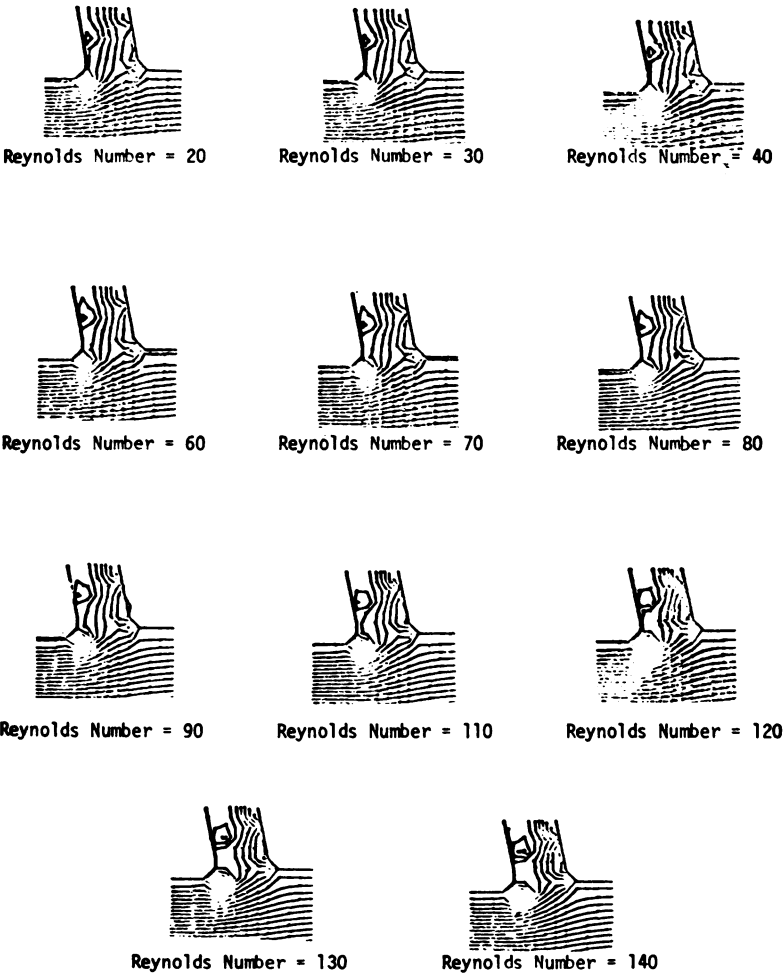


Fig. 18. Montage depicting a renal artery branching from the aorta at an upstream facing angle. Blood flow velocity was varied to show the resultant changes in a vortex.

view in a natural manner. The helmet-wearing subject can move in a volumetric space of specified size and as he moves toward the object, its apparent size and perspective appearance change. Initially, there had appeared to be no particular application for this computer tool; therefore, its use was directed towards our attempt to walk into a simulated artery. A film was the outcome of this investigation. In the film the observer walked into an aortic section, turned into a renal artery and then traced his steps (Greenfield and Vickers, et al., 1971).

As shown in Figure 20, the head mounted display consists of a head position sensor, the digital computer, a matrix multiplier, a clipping divider and the head set. The head position sensor includes concentric moving shafts between the head set and the ceiling. By their movement a certain volume of head motion is allowed. As the wearer moves, high resolution counters measure rotation along the shaft. These counters send signals to the computer for defining the observer's head position with respect to fixed room coordinates, in matrix form. Such data, plus the data that defines the coordinate values in matrix form for each point of the displayed object, are combined by the matrix multiplier equipment. The computer



Fig. 19. An observer wearing the head-mounted display equipment.

can then manipulate all coordinate values to allow the illusion that the object rotates, translates, or changes size. As the observer walks toward and into an object the clipping divider computes new end points for those object points that move out of the observer's peripheral vision, thus presenting the illusion that one has moved into the object. The head set presents the observer with synthetic objects defined by the computer's data file. Figure 21 exhibits some frames from the finished film. In another film the observer also walked into a simulated prosthetic heart valve (not shown here).

Also to be mentioned is the wand (Vickers, 1973). This unit is a hand-held rod that is ancillary to the head-mounted display equipment. It permits the user to interact with the synthetic object that is suspended in space. One points to a point in the suspended image and forms contact with that point by pressing a button on the wand. A series of such buttons acts as the communication input to the computer. The observer can then move the wand to a different position in space with the immediate result that the object is elongated, fused, or added to, as shown in Figure 22. The user can also "zoom in" for detailed study of a particular component or surface of the object.

## 6. DISCUSSION

The most ambitious phase of the overall investigation is presently being contemplated. It is one that employs all the simulation concepts seen to this point. To paraphrase the title of this paper, it will be an attempt to duplicate a detailed history of a continually forming, atherosclerotic advanced lesion with a proportionate interest in the coronary artery regime. The rationale is two-fold; not only is present knowledge of the complete growth cycle of such lesions a non-detailed, but gross view gained from non-human experiments or mortalities, but also, the importance of such coronary artery phenomena is obvious.

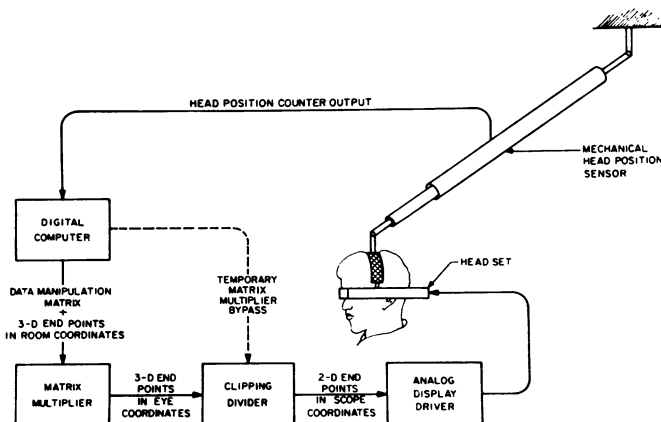


Fig. 20. Information flow components within the head-mounted display terminal.

Assume that the investigator, using the head-mounted display system, positions himself in a simulated coronary artery. He then travels to a site of predilection for the initiation of a lesion, based upon the geometrics of the chosen channel and the fluid dynamics involved. It would certainly appear that a typical portion of the coronary arterial tree is a many-times amplification of the renal and/or aortic bifurcation geometry that has been previously simulated. In turn, although not specifically discussed, certain algorithms within our present capabilities, permit the wire form arteries of Figure 21 to be shaded, smoothed and colored (Greenfield, 1972) for a more natural appearance. As the observer hovers over the point of interest, having used the rotation feature to turn internally within the natural appearing artery to face the wall, the initiation of the lesion's growth would be formed by use of memory-stored equations describing platelet diffusion theory, in conjunction with red cell augmented diffusion, via a transport mechanism (Monsler et al., 1970). The initial lesion might then appear as computer simulated in Figure 23. The observer, by command

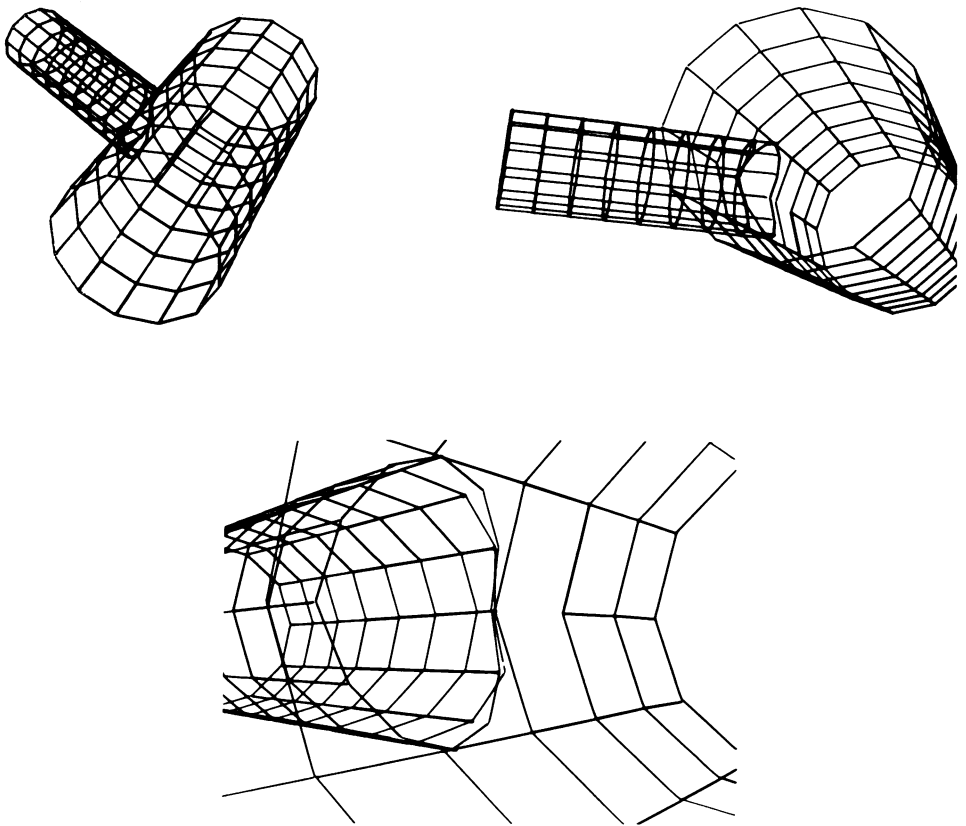


Fig. 21. Some views of the vascular configuration as simulated by the head-mounted display system. One notes the positioning of the observer within the artery, in certain frames of the film.

to the computer can rotate and zoom in to view the eventual growth at a particular surface point (see Figures 24, 25 and 26).

The asymptotic structure of platelet aggregates will be described mathematically to allow subsequent computer algorithms to be defined. A detailed, growing surface section will then be formed in conjunction with surface shading, via spline function theory. As the surface is changing shape, blood flow represented by particles would form streamlines and turbulent eddies and stasis regions would appear. Attendant stress values at various positions would appear numerically upon the graphics display screen, in conjunction with visual results and typical red blood cell damage evaluation. (All such capabilities have been exemplified in this paper.)

If the observer were able to touch the center fold of the simulated surface and then move it in an upward fashion to represent stress, the pulling action at one surface position would change the constraint values at the other surface position. Such action would denote steps in the growth cycle of a lesion. The pulling action, with its resulting stress analysis values plotted on the display, could well be performed by the "wand" in conjunction with the head-mounted display system. The new shape is then displayed in space or upon the display screen.

As the observer hovers over an area of interest, such man-machine interaction would allow continuous changes in equations for the theory to evolve and come closer to available data. If, in turn, a plaque, for example, does not correctly build up piecewise according to known data, one can immediately erase a portion of the simulation. By computer command the flow can be initiated again about the reshaped plaque section. If the plaque, in its formulative details, is seen to approximate some known part of the growth cycle, it is then assumed that the mathematical equations in the theory are correct. The sum of the interim steps that result will be compared to viewed lesions seen in animal experimentations or cadavers. At

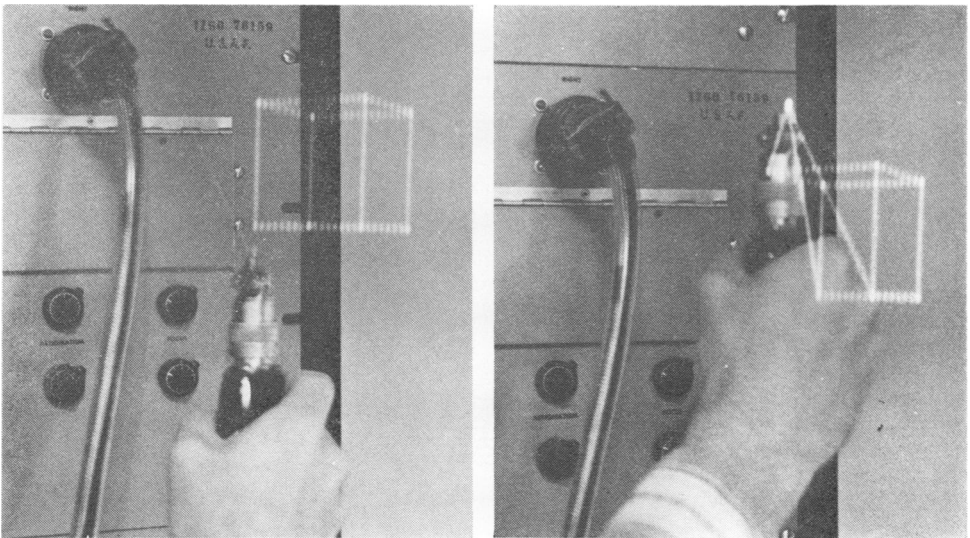


Fig. 22. A simple cube, positioned and varied in shape, by use of the wand.

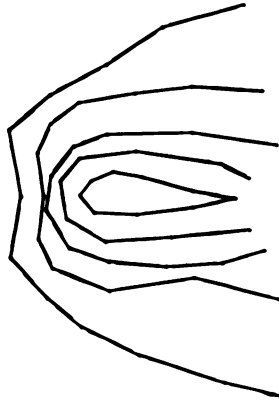


Fig. 23. Idealized plaque growth, computer simulated.

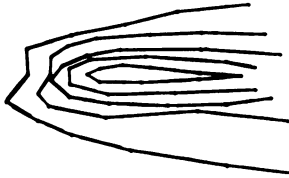


Fig. 24. Simulated plaque, rotated approximately 35 degrees about the x axis.

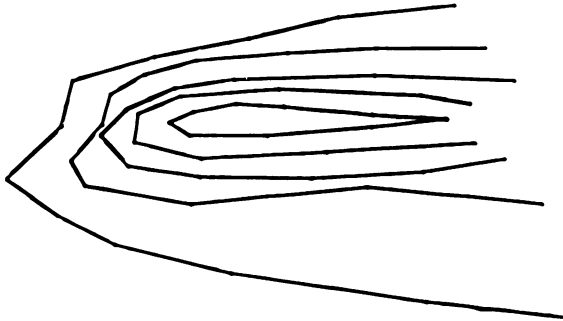


Fig. 25. Previous simulation, enlarged as the observer "zooms" in toward the plaque.



Fig. 26. Computer rotation of a simulated plaque to a degree that would allow cross-sectional viewing before the growth cycle was varied.

present, we are performing experimental stress studies in a fluid about a model lesion so as to attempt verification of the computer simulations. If the procedure is successful, parts or eventually the whole of the formation of an atherosclerotic lesion would be displayed in minutes—equivalent to natural atheroma buildup which takes years to develop. Varying conditions and assumptions could be quickly interchanged and evaluated.

This investigator is convinced that fluid dynamic concepts and numerical analysis techniques have important roles in the studies of hemodynamic phenomena. The use of computer graphics allows acquisition of information by man-machine interaction not previously available. The task of obtaining results is still arduous and the continuous development of this interdisciplinary technique is required.

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